

Global trends in carbon dioxide (CO₂) emissions from fuel combustion in marine fisheries from 1950 to 2016



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ABSTRACT

Using the *Sea Around Us* global catch and effort databases (www.seaaroundus.org), this study presents time series estimates (1950–2016) of total CO₂ emissions and emissions intensity (CO₂ emissions per unit of catch) from the combustion of fuel in global marine fisheries by fishing sector, as well as a regional comparison of fuel use intensity for 2011. In 2016, total CO₂ emissions of the industrial fishing sector were 159 million tonnes compared to 39 million tonnes in 1950. In contrast, the small-scale fishing sector emitted 48 million tonnes in 2016, compared to only 8 million tonnes in 1950. Industrial CO₂ emissions intensity was estimated to be 2.0 tCO₂/tcatch⁻¹ in 2016 compared to 1.8 tCO₂/tcatch⁻¹ for the small-scale sector in the same year. A previous study, using different methods, estimated global CO₂ emissions from fishing to be 112 million tonnes in 2011. Geographical comparisons suggest that the differences between global estimates are explained by regional variation in fuel use intensity and the inclusion of unreported catch and effort data in our estimate. Supplementing fuel use intensity data for one region to that of another with considerably different fisheries may result in misrepresenting fuel use intensity and subsequently CO₂ emissions. Our analysis provides insights into changing trends in CO₂ emissions from marine fishing and highlights the potential importance of this industry as part of global CO₂ reduction strategies.

1. Introduction

Research on fisheries and climate change has primarily focused on how fisheries will be affected by climate change, for example, climate change will likely decrease primary production, redistribute marine resources and increase the economic strain and vulnerability of already vulnerable countries [e.g., 1–5]. At present, global greenhouse gas (GHG) emissions are tracking the high-risk scenarios modelled by the Intergovernmental Panel on Climate Change (IPCC), which suggests that 38 billion tonnes of Carbon dioxide (CO₂) emissions were released into the atmosphere in 2014 [6]. Furthermore, the average increase in CO₂ emissions has been 2.2% since 2000 indicating that CO₂ production per capita is increasing [6]. Reducing GHG emissions and mitigating the effects of climate change depends on our understanding of what sectors are significant contributors to CO₂ emissions, and where reduction strategies can be effectively implemented. The marine fishing industry relies heavily on the use of fossil fuels, i.e., fuel costs can account for up to 60% of total fishing costs [7,8]. Previously published estimates suggest that the industrial fishing sector is a significant

contributor to global CO₂ emissions [9–14] but have not yet addressed how CO₂ emissions from fishing have changed over time, nor the contribution of CO₂ emissions from fisheries whose catch is partially or completely unreported. As such, this study had four primary goals:

1. Account for CO₂ emissions from both reported and unreported fisheries, for both the industrial and small-scale fishing sectors;
2. Provide a global trend, by sector, of total CO₂ emissions from the combustion of fuel in marine fisheries from 1950 to 2016;
3. Estimate emissions intensity (CO₂ emissions per tonne of catch) by sector for the same time period and;
4. Compare global and regional Fuel Use Intensity (FUI) and CO₂ emissions estimated by different methodologies.

2. Methods

Fishing is a fuel intensive activity and the amount of fuel used can be estimated by effort deployed by motorised fishing fleets; this approach is particularly useful when there is a dearth of data on the fuel

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required to catch a given quantity of fish (as is common in small-scale fisheries, particularly in developing countries). Here, fishing effort data were compiled from the bottom up using a reconstruction approach [see 15–18] and are independent of catch data. Detailed methods are presented in the following sections.

2.1. Fishing effort data

The number of fishing vessels for each country were reconstructed by fleet, with a fleet being defined by fishing country, sector, gear, length class and motorization. The engine capacity per fishing vessel (kW) per fleet was determined by length (m) and motorization (Table 1).

In accordance with the global catch reconstruction approach [15,19], a single, standardized global definition for the fishing sectors was not used; rather country-specific definitions were applied to allocated fleet data to fishing sectors. This approach was chosen because there is no standardized definition of what is small-scale¹ and what is industrial, as the transition point from small-scale to industrial is not always the same in every country. When no country-specific definition was available, three main factors were used to determine fishing sector:

1. Gear – any vessels, regardless of size, that deploy mechanized gears such a bottom trawl gear were assumed to be industrial;
2. Vessel size – Any vessels less than 15.9 m were considered to be small-scale;
3. Motorization – Any non-motorised vessels were assumed to be small-scale.

All vessels were placed in length classes and the mean engine power (kW) per boat within each length class was used to estimate fuel use (Table 1). Care was taken to derive length classes that became progressively wider in order to account for greater variability in the engine power (kW) of larger vessels [20]. Consequently, the arithmetic mean of length was used only for the two smallest length classes, whereas the geometric mean was used for the larger (and broader) length classes. Vessel length (m) was used to estimate engine capacity (kW) for each vessel in a given fleet because it was the only variable available and applicable to all different types of fishing vessels that is correlated with engine capacity. Traditionally, gross tonnage (GT) was used as a main measure of vessel capacity. However, GT describes the internal volume of a vessel and is only reported for, and applicable to, decked vessels greater than 24.9 m [21,22]. Many of the world's smaller industrial fishing vessels and likely all or most of the small-scale vessels do not meet these criteria. Moreover, GT is more useful for cargo vessels whose internal volume accounts for the carrying capacity of freight [23].

Effective fishing effort by country is therefore defined here as the product of the engine capacity of the number of boats in a fleet segment and the number of days spent at sea [24,25]. The number of days at sea was determined via literature searches during individual country fishing effort reconstruction. In those instances where fleet-specific data were not found, the number of days at sea was estimated by gear type and region (Table 2) as estimated in [20]. The core unit of effective fishing effort used here is kW-day in a given year [24,25]. Linear interpolation was used to estimate fishing effort for years where data were not available.

2.2. Fuel consumption

Carbon dioxide emissions by marine vessels are directly correlated with fuel consumption, and it is possible to estimate average fuel consumption from fishing effort [9,26,27], despite operational and

¹ Small-scale fishing in this study refers to both artisanal (i.e., small-scale, commercial) and subsistence fishing (small-scale, non-commercial).

technological factors that may impact individual vessel fuel use. Many vessels continue to operate with engines that are decades old [7,28], and implementation of fuel saving technologies varies depending on fishing country, fishing sector, price of fuel, status of the fishery and the profitability of fish stocks targeted [eg., 29,30]. Nevertheless, potential changes in engine efficiency over time were considered here, as this is likely to affect the amount of CO₂ emitted. In order to convert effective fishing effort (kW-day) to fuel consumption, three variables were required: a specific fuel consumption rate (SFR), a fuel coefficient (FC) to account for changes in fuel efficiency over time, and the number of hours engines run per fishing day (H).

2.2.1. Specific fuel consumption rate (SFR)

The fuel used while fishing can vary greatly between individual vessels as a result of many factors, including the gear being used, weather, cost of fuel and operator experience [28,31,32]. An estimate of SFR that would apply to many different vessel types was determined by the dominant engine type used within each fishing sector. Most engine-powered fishing vessels are powered with either a diesel engine (most common in the industrial fleets) or a spark-ignited Otto cycle engine, i.e., a gasoline (petroleum) powered outboard engine characteristic of many small-scale fisheries [33].

The industrial sector was assumed to be exclusively equipped with marine diesel engines due to the larger sizes of vessels and the heavier, often active gear types deployed (e.g., trawls). A study analyzing registered vessels, including fishing, cargo and military vessels, found that over 70% of large vessels are equipped with diesel engines [33]. Fuel consumption is also affected by the type of diesel oil used. In general, there are three categories of diesel oil used in the marine industry: distillate, intermediate and residual [34]. The marine industry usually refers to the intermediate category simply as “marine diesel” and it was the most common fuel type encountered during all data searches (Table 3). The average, standardized SFR for industrial fishing vessels was estimated to be 0.0002 tFuel·kWh⁻¹ (Table 3).

The engine characteristics and use patterns for small-scale fisheries generally differ from industrial vessels; engines are smaller and are often gasoline (petroleum) fueled. Some literature does exist on fuel use in small-scale fisheries, and is often reported in litres per kg of catch (e.g., [43–45]). Without fuel density, it was not possible to convert litre estimates of fuel use in small-scale fisheries to tonnes of fuel burned per kWh. As a result, the SFR used for the small-scale fishing sector in the present study was derived from fuel use by recreational fisheries. Recreational fisheries differ from artisanal and subsistence fisheries in many ways, however, basic engine characteristics were assumed to be similar, i.e., gasoline fuel of either a 2 or 4 stroke outboard engine. In 2000, SFRs for the two engine types were reported to be 0.0004 tFuel·kWh⁻¹ and 0.00035 tFuel·kWh⁻¹, respectively (Table 3) [38]. The more conservative SFR of 0.00035 tFuel·kWh⁻¹ was used here for all small-scale vessels (Table 4). It is evident that more research and detailed data sets on engine types, sizes and fuel consumption are needed for small-scale fisheries around the world.

2.2.2. Fuel coefficient (FC)

The Specific Fuel Rates (SFRs) for industrial and small-scale vessels represent the estimation of fuel consumption at a given point in time; however, engine efficiency has changed with advances in new technology since the 1950s. In order to account for changes in SFR over time, a Fuel Coefficient (FC) was derived. Yanmar, an international builder and supplier of marine engines since 1912 (www.yanmarmarine.eu), provided fuel consumption data for the years 1960, 1974, 1980, 1985, 1989, 1996 and 2002. These data were used to estimate SFRs annually from 1950 to 2016, using linear interpolation between raw data points. The SFR values for 1950–1959 were assumed to be the same as the 1960 reported value. Similarly, the SFR from 2003 to 2016 were assumed to be constant at the 2002 raw data point. The year 2000 was used as a benchmark, i.e., the FC for the year 2000 was

Table 1
Capacity of motorised and non-motorised fishing vessels by length class.

Length class	Range (m)	Mean length ^a (m)	Sector – motorised ^b	Capacity –motorised (kW·boat ⁻¹)	Sector – non-motorised ^c	Capacity – non-motorised (kW·boat ⁻¹)
1	< 7.9	4.5	Small -scale	9.11	Small -scale	0.37
2	8 – 15.9	11.3	Small -scale	58.7	Small -scale	0.75
3	16 – 24.9	20.0	Industrial	185	Small -scale	1.12
4	25 – 49.9	35.4	Industrial	587	NA	NA ^d
5	50 – 99.9	70.7	Industrial	2383	NA	NA ^d
6	100–150	122.5	Industrial	7235	NA	NA ^d

^a The arithmetic mean was used for length class 3 and up. The geometric mean was used for length class 1 and 2.

^b If no country specific information was found all motorised fleets less than length class 2 were assumed to be small-scale. All motorised fleets in length class and greater were assumed to be industrial.

^c All non-motorised vessels were assumed to belong to the small – scale sector.

^d There were no fleets with non-motorised vessels greater than length class 3.

Table 2
Number of days at sea (i.e., fishing trip days) by marine fishing vessels as estimated in Anticamara et al. [20]^a.

Gear	Africa	Asia	Australia & Oceania	Europe	North America	South America
Gillnet	140	171	171	155	155	155
Hook and Line	243	297	297	270	270	270
Longline	274	334	334	304	304	304
Purse Seine	159	195	195	177	177	177
Trap	104	128	128	116	116	116
Trawls	180	220	220	200	200	200
Unknown	175	213	213	194	194	194

^a These values were used in the absence of fleet- and or country-specific data.

Table 3
Specific Fuel Rate (SFR) and CO₂ Emissions Factors (EF) by reference.

Sector	SFR (g·kWh ⁻¹)	EF (tCO ₂ ·tFuel ⁻¹)	Year(s)	Fuel type	Reference
Industrial	215	3.179	2004	Marine diesel	[35]
Industrial	212	3.170	2004	Marine diesel	[27]
Industrial	200 – 240	–	1925 – 2002	Marine diesel	[36]
Industrial	–	3.170	1999	Marine diesel	[37]
Industrial	170 – 260	–	1990 – 2005	Marine diesel	[38]
Small-scale	400	–	2008	Petroleum	[39]
Small-scale	350	–	2008	Petroleum	[39]
Small-scale	–	2.3	2014	Petroleum	[40]
Small-scale	–	2.4	2014	Petroleum	[41]
Small-scale	–	3.006	2014	Petroleum	[42]

Table 4
Values used in the present study for each variable to estimate CO₂ emissions from fishing effort.

Sector	SFR (tFuel·kWh ⁻¹)	Emissions Factor (tCO ₂ ·tFuel ⁻¹)	Trip duration (hours·day ⁻¹)	Engine run (hours)
Industrial	0.00020	3.17	24	24
Small – scale	0.00035	3.01	6	4

set at 1. The relative FCs over times were then derived for each year to adjust for the changes in SFR over time (Table 5). The FC is a relative marker describing changes in engine fuel efficiency and is therefore a dimensionless measure. The same annual FCs were used for all fishing sectors, thus assuming that fuel efficiency changed equally in both diesel and gasoline powered engines. This assumption requires further research.

2.2.3. Engine run time (H)

The number of active engine run time hours per day of fishing (H) varies greatly between fleets, not only regionally but also across fishing sectors, gear types and seasons. Industrial vessels, for example, generally run their main engines 24 h a day while at sea [46] whereas artisanal fishers are likely to return home at the end of each daily

fishing trip and turn off their engines after setting their fishing gears. Gear may also greatly affect engine run time; some more active gears such as trolling require the use of the main engine during fishing whereas other gears (e.g., traps, gill nets, hand lines) only require the engine to run while traveling to/from fishing grounds and during the setting and/or retrieving of the gear, but not necessarily during the active fishing phase. In concordance with previously published fisheries fuel consumption studies, an estimate of mean hours of engine run time was applied specific to fishing sector. The industrial sector was assumed to run their engines 24 h for every day at sea [e.g., 29,39–42] (Table 4). Fishing operations do not occur at all times during an industrial fishing trip. However, industrial vessels are in transit between fishing sites or steaming to or from ports when not actively fishing, in addition to the need for electrical power for on board refrigeration.

The number of hours engines are run in the small-scale fishing sector is highly variable (Fig. 1). A literature search was conducted and 98 estimates of trip duration (in hours) were found (Appendix A); on average, artisanal fishers undertake fishing trips of 5–6 h per fishing day (Fig. 1). The number of engine run hours during each fishing trip depends on various factors, for example, distance to fishing grounds, gear being used, cost of fuel and weather/ocean conditions. In the present study, we assumed that engines on small-scale vessels were run for two thirds of the fishing trip length, or 4 h per fishing trip (Table 4).

2.3. Carbon dioxide emissions factor (EF)

The amount of CO₂ emissions, or the emissions factor (EF), varies by fuel type. Generally less refined and heavier fuel types (e.g., marine

Table 5
Derived relative Fuel Coefficient (FC) used to account for changes in engine fuel efficiency per year ^a. The year 2000 was set as anchor point with FC = 1.0.

Year	Fuel coefficient	Year	Fuel coefficient	Year	Fuel coefficient
1950	1.21	1973	1.13	1996	1.01
1951	1.21	1974	1.12	1997	1.01
1952	1.20	1975	1.11	1998	1.01
1953	1.20	1976	1.11	1999	1.00
1954	1.20	1977	1.10	2000	1.00
1955	1.20	1978	1.09	2001	1.00
1956	1.20	1979	1.09	2002	1.00
1957	1.20	1980	1.08	2003	1.00
1958	1.20	1981	1.07	2004	0.99
1959	1.19	1982	1.07	2005	0.99
1960	1.19	1983	1.06	2006	0.99
1961	1.19	1984	1.06	2007	0.99
1962	1.19	1985	1.05	2008	0.99
1963	1.18	1986	1.05	2009	0.99
1964	1.18	1987	1.04	2010	0.99
1965	1.18	1988	1.04	2011	0.99
1966	1.18	1989	1.04	2012	0.99
1967	1.17	1990	1.03	2013	0.99
1968	1.16	1991	1.03	2014	0.99
1969	1.16	1992	1.03	2015	0.99
1970	1.15	1993	1.02	2016	0.99
1971	1.14	1994	1.02		
1972	1.14	1995	1.02		

^a FC is a relative marker describing change in engine fuel efficiency over time and is therefore a dimension less measure.

diesel) generate higher emissions than distilled and refined fuels (e.g., 4-stroke engine gasoline fuel). Most research on this topic has focused on the emissions of road-based fuel types [e.g., 43–45,47,49–51], although more recently, emissions have been reported for marine diesel engines [eg. 12,14,48,52,53]. The EF used in this study for marine diesel was 3.17 t of CO₂ per tonne of fuel (tCO₂tfuel⁻¹), while the emissions factor used for gasoline was 3.01 tCO₂tfuel⁻¹ (Table 3). CO₂ emissions per fishing country by fishing sector were thus calculated by multiplying the annual effective fishing effort per sector per country by the fuel consumed per sector and by the appropriate emissions factors. Global CO₂ emissions by sector were then estimated by summing all countries annually from 1950 to 2016. Results are also presented by broad geographic region for the year 2011: Africa, Asia (excluding China), China, Europe, Latin America, North America, and Oceania.

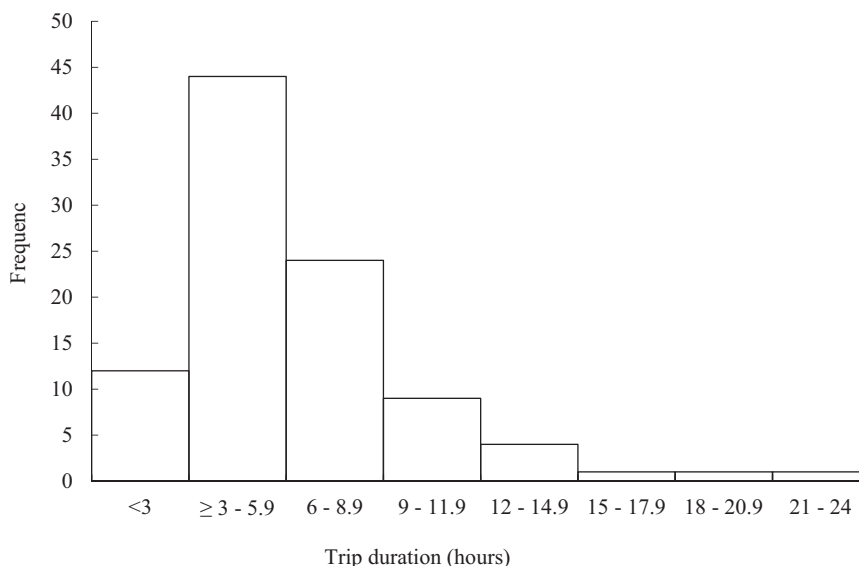


Fig. 1. Frequency of trip duration (hours; mean = 6, n = 60). See Appendix A for trip duration by reference.

2.4. Emissions intensity

Emissions intensity (tCO₂tcatch⁻¹) for each fishing sector was subsequently derived by taking the quotient of CO₂ emissions and reconstructed catch for each sector [15,53]. Global catches per country by fishing sector for all years between 1950 and 2014 were taken from the global *Sea Around Us* catch database publicly available at www.seaaroundus.org [15,19,53]. As the reconstructed catch data for most countries have not yet been updated to 2016, the respective value for 2014 was carried forward. Emissions intensity for the industrial sector was derived both with and without the catch of Peruvian anchoveta (*Engraulis ringens*).

2.5. Missing fishing effort

The fishing effort database [24] of the *Sea Around Us* (www.seaaroundus.org), currently includes data on 149 marine fishing countries from 1950 to 2016, which account for over 98% of global reconstructed catches [15,53]. In order to account for the remaining < 2% of catch, fishing effort was estimated by multiplying the fishing effort by fishing sector for the countries with effort data by a sector-specific extrapolation factor (EF). The EF was derived by taking the quotient of catch by fishing sector of the countries for which effort data had been compiled and the catch for all countries.

2.6. Comparison of fuel use and carbon dioxide emissions with Parker et al. [14]

Parker et al. [14] estimated CO₂ emissions using fuel use intensity (litres per tonne of catch) derived from the Fuel Use and Energy Database (FEUD; [13]). FEUD contains catch and country specific fuel use values; these values were used to estimate emissions intensity per unit of catch which was then multiplied by global catch as presented by Watson [54]. Parker et al. [14] presented their results globally and by major geographic regions: Africa, Asia (excluding China), China, Europe, North America, Latin America and Oceania. The global catch data used in Parker et al. [14], however, differs from what is included in the *Sea Around Us* globally reconstructed catch database. For the same year (2011) and regions we compared FUI, EI and total CO₂ emissions by fishing in four different scenarios:

1. Estimated from fishing effort using *Sea Around Us* reconstructed database (methods described thus far);

2. Original estimate in Parker et al. [14] adjusted to account for CO₂ emissions originating only from the combustion of fuel from fishing;
3. Using the 'catch-based FUI' estimates of Parker et al. [14], multiplied by *Sea Around Us* global reconstructed catch; and
4. Calibrating our 'effort-based FUI' estimate using the catch-based FUI of Parker et al. [14] regions with the top two number entries in FEUD (Europe and North America) multiplied by *Sea Around Us* global reconstructed catch. Note that Oceania was excluded from the recalibration estimate because the data for Oceania in Parker et al. [14] represent mostly trawl fisheries (highly fuel intensive and not representative for most of the Oceania region, especially their small-scale fisheries) and was the only region where the FUI by Parker et al. [14] was higher than FUI of the present study prior to recalibration.

Scenario four was designed to account for the possible systematic over estimation of effort-based FUI if one or several of our assumptions were incorrect. It is thought that the catch-based FUI for Europe and North America are likely to be accurate and representative of fisheries in these regions because they have a high number of independent estimates in FEUD. Therefore, the proportion of the average difference between catch-based FUI [14] and effort-based FUI for these two regions was used to calibrate effort-based FUI for all regions. The values from this calculation were applied to the entire time period, and are the CO₂ emissions values reported as the final result.

3. Results

3.1. Global carbon dioxide emissions

Global CO₂ emissions from the main engine combustion of fuel in marine fisheries amounted to approximately 207 million t of CO₂ in 2016, compared to 47 million t of CO₂ in 1950 (Fig. 2). In 2016, the industrial sector released around 159 million t of CO₂, i.e., 4.1 times more than in 1950 and accounted for 77% of global CO₂ emissions from marine fisheries (Fig. 2). In comparison, the small-scale sector released around 47 million t of CO₂ in 2016, 5.8 times more than in 1950 (Fig. 2). CO₂ emissions in both sectors continued to increase after the mid-1990s, despite declining global catches 9F.

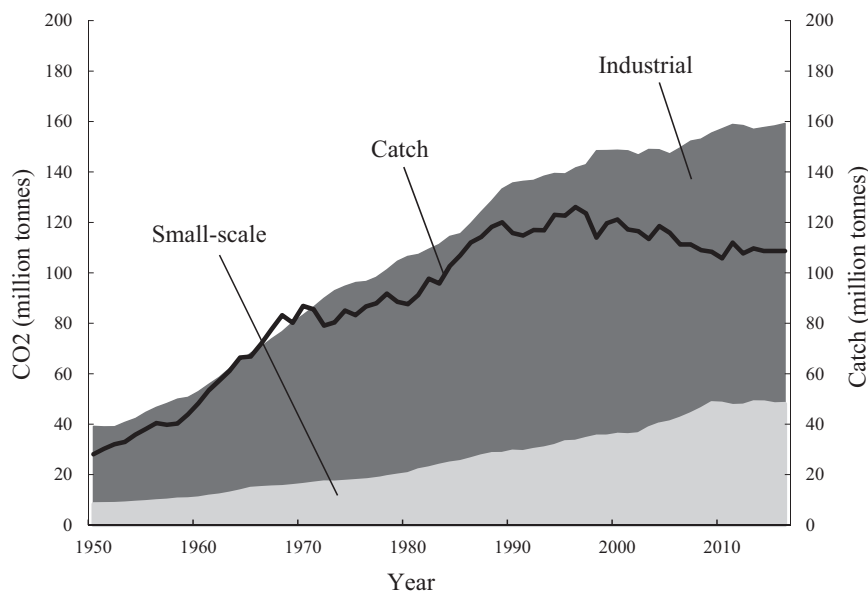


Fig. 2. Total CO₂ emissions by fishing sector, and total reconstructed global catch.

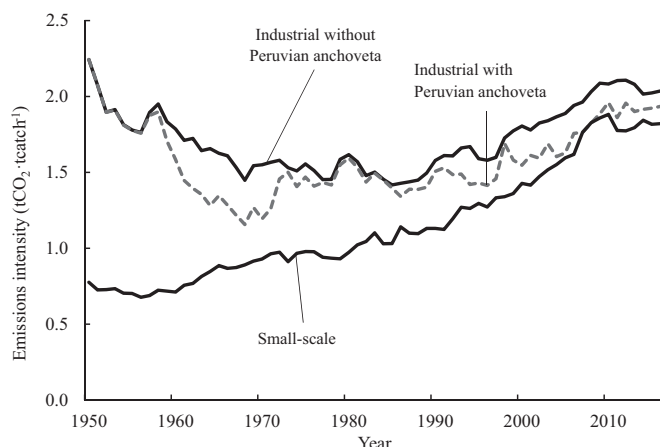


Fig. 3. CO₂ emissions intensity of global fisheries, by major fishing sectors. The industrial sector is shown with and without the highly variable Peruvian anchoveta catches.

3.2. Emissions intensity

The industrial fishing sector demonstrated a substantial decrease in the emissions intensity from 1950 to the mid-late 1960s (with and without the highly variable Peruvian anchoveta catches), from 2.2 tCO₂/tcatch⁻¹ to 1.4 tCO₂/tcatch⁻¹ (1.2 tCO₂/tcatch⁻¹ with anchoveta; Fig. 3). It fluctuated thereafter until the mid-late 1990s, after which it started to increase again to reach 2.0 tCO₂/tcatch⁻¹ by 2016 (1.9 tCO₂/tcatch⁻¹ with anchoveta; Fig. 3). In contrast, the emissions intensity of the small-scale sector has been steadily increasing throughout the time series, and by 2016 was 2.3 times what it was in 1950 (1.8 tCO₂/tcatch⁻¹ and 0.78 tCO₂/tcatch⁻¹ respectively; Fig. 3). In 1950, the difference in emissions intensity between the two fishing sectors was considerable – the industrial sector was nearly three times higher; however, present day emissions intensity between the two sectors is much more similar and differs only by around 10% (Fig. 3).

3.3. Comparison of fuel use intensity, emissions intensity and total carbon dioxide emissions to Parker et al. (2018)

For the year 2011, our study estimated global average fuel use

Table 6Comparison between Catch, Fuel Use Intensity (FUI), Emissions Intensity (EI) and total CO₂ emissions comparison of Parker et al. (2018; P) and this contribution (G).

Region (n) ^a	Catch (million t)			FUI (tFuel-tCatch ⁻¹)			EI (tCO ₂ -tCatch ⁻¹)		CO ₂ Emissions (million t)			
	P	G		P	G	G Standardized ^c	P ^d	G	P	P Standardized ^e	G	G Standardized ^f
		Landings ^b	Reported									
Africa (7)	5	5.1	2.7	0.35	0.93	0.69	1.2	2.9	5.7	9.0	22.7	16.8
Asia (excl. China) (< 34) ^g	28	25.6	13.5	0.50	1.19	0.88	1.6	3.7	44.6	62.2	145.2	107.5
China (< 34) ^g	13	13.6	1.7	0.73	1.07	0.80	2.4	3.4	30.6	35.9	51.7	38.3
Europe (640)	12	13.4	6.5	0.35	0.49	0.36	1.1	1.5	13.0	21.6	30.6	22.6
Latin America (2) ^h	16	14.6	3.3	0.21	0.22	0.16	0.6	0.6	10.2	11.4	10.1	7.5
North America (115) ^h	6	8.9	2.7	0.34	0.45	0.33	1.1	1.4	6.5	12.6	16.3	12.1
Oceania (303)	1	0.9	0.2	0.57	0.41	0.31	1.8	1.3	1.8	2.1	1.5	1.1
Global (1126)	81	82.1	30.7	0.44	0.79	0.59	1.4	2.5	111.9	157.9	280.4	207.6

^a The number of FUI estimates used in Parker et al. [14] as reported in Parker and Tyedmers (2015) for each region are given in brackets; n for Asia includes China.

^b Parker et al., [14] presented reported and unreported as a combined total labelled as “landings”.

^c Catch-based using Parker et al. [14] to calibrate *Sea Around Us* FUI by region.

^d EI from Parker et al., [14] has been adjusted to include only emissions directly from fishing, therefore the emissions from up – and downstream processes have been excluded.

^e Total CO₂ emissions (million t) using FUI estimates by Parker et al., [14] multiplied by *Sea Around Us* total reconstructed catch data.

^f Total CO₂ emissions (million t) using FUI estimates by Parker et al., [14] for Europe and North America to calibrate *Sea Around Us* FUI by region.

^g Parker and Tyedmers (2015) reports the number of FUI records for Asia (excluding China) and China as a combined total labelled as “Asia”. Therefore each of these regions has less than 34 FUI records.

^h The countries included in each region were not defined in Parker et al., [14]. The region assignment was assumed to be the same as the *Sea Around Us* and therefore Latin America excludes Mexico and North America includes both Mexico and the Caribbean.

intensity (FUI) for marine fisheries as 0.59 tFuel-tcatch⁻¹, which was 1.3 times what was reported as the global average in Parker et al. [14] (0.44 tFuel-tcatch⁻¹; Table 6). There are, however, considerable regional differences in estimated FUI between methods (Table 6). Effort-based FUI was considerably higher (greater than 30%) in three regions: Africa, Asia (excluding China) and China (Table 6). In contrast, catch-based FUI in [14] was greater both Latin America (24%) and Oceania (46% greater; Table 6).

CO₂ emissions from fishing were previously reported to be 112 million t in 2011 [14]; however the global catch data used in Parker et al. [14] differs from what is included in the *Sea Around Us* reconstructed catch database. When the reconstructed unreported catches are included, CO₂ emissions using the same methods of Parker et al. [14] are estimated to be 158 million t in the same year, i.e., accounting for unreported fisheries raises total CO₂ emissions by 41% (Table 6). CO₂ emissions estimated from fishing effort with the FUI calibrated using the regions where Parker et al. [14] had abundant catch-based FUI data (Europe and North America), total CO₂ emissions are estimated to be 208 million t, or 30% more than what was estimated using catch-based FUI (Table 6).

4. Discussion

To effectively reduce CO₂ emissions it is necessary to recognize key contributors and identify ready targets for effective reduction plans, particularly those with the greatest impact. The extent to which marine fisheries, primarily from the combustion of fuel, contribute to global CO₂ emissions both over time and space was unknown until recently (e.g., [12,14]). The current study presents several main findings both with regards to the global contribution of marine fisheries to CO₂ emissions, and their regional variation. Regional variation of CO₂ emissions estimates will occur whether catch (as per Parker et al. [14]) or fishing effort (present study) is used to estimate fuel use intensity. Our findings for CO₂ emissions are higher than what has previously been reported. The majority of the difference between our study and the previously published estimate [14] may be explained at the regional level: Africa, Asia (excluding China) and China were all found to have much higher FUI when derived via locally reconstructed fishing effort data compared to catch-based FUI estimates. Similarly the mean catch-based FUI estimated by Parker et al. [14] for Latin America was

substantially higher than that estimated from fishing effort. We suggest that the difference in FUI for these regions is a result of Parker et al. [14] using FUI data from other regions to supplement areas where catch-based FUI estimates were not available. The Fuel Use and Energy Database (FEUD; [13]) used by Parker et al. [14] contains a total of 1126 records of catch –based FUI globally, however there are only 34 records of FUI for all of Asia (in that case including China), 7 for Africa and only 2 for Latin America. In contrast, the number of catch-based FUI records for Europe was 640, followed by Oceania (303) and North America (115) [13]. As a result, data from regions where there were more records available to estimate catch-based FUI were used to supplement and substitute in regions where catch-based FUI was not well covered [14]. Latin America's catch, for example, is dominated by the very efficient purse seine fishery for Peruvian anchoveta, which may lead to over estimating FUI for this region if data from other regions are used in lieu. In contrast the remaining “data poor” regions engage in many highly fuel intensive fishing practices such as trawling leading to catch-based FUI to be underestimated.

The FUI data for Oceania exhibited a different trend than that of the other regions; Parker et al. [14] estimated a higher catch-based FUI but FEUD has a high number of records for this region (303; [13]). Oceania's catch-based FUI is characterized by trawling for crustaceans particularly from Australia – this fishery is known to be very fuel intensive and inefficient [14]. It is possible that when a region's FUI data source is highly skewed by one gear type, using an average FUI by catch may be inaccurate at the regional level. The number of entries in FEUD by country was not available for this analysis, but it is likely that Australia and New Zealand are over-represented in comparison to the many small island countries in this region. If the catch-based FUI estimates for Australia and New Zealand were used to again supplement FUI for other countries within this region, given that Australia has the highest catch-based FUI in the world, it is likely that using Australia's data in other countries in this region would result in an over estimate of FUI. To investigate Oceania further, it would be useful to estimate FUI excluding Australia and New Zealand. While the *Sea Around Us* fishing effort database does allow for this level of detail, the published version of catch-based FUI does not allow for this type of comparison. The results indicate that both methods, effort-and catch-based FUI, are useful depending on the goals of the study and what data are readily available. Furthermore, when used in conjunction, both methods can be used to

validate each other and identify areas of potential uncertainty. Both sets of results suggest that FUI in the small-scale sector remains highly uncertain and more research focusing on practices in regions with little data, for example Africa, are needed.

This study presents data on FUI and CO₂ emissions from the world's small-scale fishing fleet for the first time. It was found that this sector, consisting of both artisanal and subsistence fishing, contributes approximately 25% of annual global CO₂ emissions and, in more recent years, has an emissions intensity similar to that of the industrial sector. The relative CO₂ emissions of the small-scale fisheries sector are commensurate with the approximately 25% of global catches that are taken by small-scale fisheries [15]. Changes over time in the absolute contribution of CO₂ emissions in the small-scale sector are likely driven by increases in motorization of small-scale vessels. Changes in emissions intensity, however, are likely a result of multiple factors, for example the distance travelled by small-scale fishers has increased along many coastlines but catches have not increased to the same extent.

This study was limited in its scope to CO₂ emissions from the combustion of fuel during fishing and did not account for up- or downstream CO₂ emissions of the larger fisheries economic sector. Emissions from sources other than fuel are likely higher for the industrial sector, although more Life-Cycle Assessment (LCA) research on small-scale fisheries is called for. Refrigerant loss, not assessed in this study, has been identified as a significant non-fuel related key source of emissions from fishing [14,55,56]; this form of emissions is relevant to industrial fishing practices only. Similarly, downstream emissions from processing and the often global marketing and distribution of industrial catch are likely to be higher in industrial fisheries – although increasingly small-scale fisheries are beginning to also supply global export markets. If these other factors were to be incorporated into the calculations, the difference in emissions intensity between the two sectors may increase.

Fisheries are likely candidates for CO₂ emission reduction plans, as many fishers may be motivated by the cost of fuel to reduce the major output source of CO₂. Our results suggest that it is important to determine the primary policy goals at the local level. Small-scale fisheries in absolute terms are estimated to contribute less than the industrial sector, yet have a similar emission intensity. The results suggest then,

for example, if a fleet of ten 12 m vessels were removed and replaced with one 35 m vessel, both emissions intensity and total CO₂ emissions from the fleet would remain similar. In contrast if the goal was to reduce emissions intensity and the region is characterized by small-scale fishers it may be appropriate to implement a diesel engine implementation program; however, it would be essential to not unintentionally increase fishing capacity of these vessels. It is therefore important to understand local fleet dynamics prior to developing and or implementing CO₂ emissions reduction strategies. Potential policy action with regards to sector specific CO₂ reduction measures should, however, take into account the social objectives of fisheries management and policy, which tend to favour small-scale fisheries for their higher employment and better livelihood support [57].

5. Conclusion

Our study provided spatial and temporal data of CO₂ emissions from marine fishing in the industrial and small-scale sector, including for unreported fisheries, based on bottom-up reconstructed global fishing effort data. CO₂ emissions by global fisheries, both in absolute terms and as emissions intensity, were found to be considerably higher than previously suggested. Regional variation exists in fuel use intensity, and we suggest that supplementing data from well-researched regions for regions where data are sparse should be used with considerable caution. There is a need for the international community to recognize marine fishing as a significant contributor of total CO₂ emissions, and develop strategies and policies that consider local fleet dynamics.

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Appendix A. Trip duration (h) for small-scale fisheries by reference

Reference	Region	Trip Duration (h)	Fishery Details
[58]	Netherland Antilles	5.5	Handlines Trolling
[59]	Netherland Antilles	5.92	Mixed
[60]	Belize	7	Handlines Fish Pots
[61]	Belize	8	Conch Diving
[62]	Belize	4.1	Reef Fishing
[62]	Belize	9	Deepwater Fishing
[62]	Belize	6	Hook and Line
[63]	Soloman Islands	1.2	Mixed
[63]	Soloman Islands	3	Mixed
[64]	Costa Rica	4	Mixed
[64]	Costa Rica	6	Mixed
[65]	Puerto Rico	5.6	Trap
[65]	St Thomas and St John	9.1	Trap
[65]	St Croix	5.6	Trap
[66]	Dominica	1–7	Mixed
[67]	Dominica	6.9–10.9	Mixed
[68]	Dominican Republic	8–10	Mixed
[69]	Dominican Republic	5	Mixed
[69]	Dominican Republic	2–4	Mixed
[70]	Dominican Republic	2–4	Non-Motorised
[70]	Dominican Republic	5–15	Motorised
[71]	El Salvador	4	Mixed
[72]	Fiji	6–10	Mixed – Motorised
[73]	Fiji	3.6–7.25	Finfish – Sheltered
[73]	Fiji	2.5–5.18	Finfish – Lagoon
[73]	Fiji	2.75–6.75	Finfish – Outer reef
[73]	Fiji	2.86–5.5	Finfish – Passage

[73]	Fiji	3–5	Invertebrates – Mangroves
[73]	Fiji	1–6.1	Invertebrates – Reef
[73]	Fiji	3–4.8	Invertebrates - Intertidal
[73]	Fiji	4.7–5.75	Lobster
[74]	Fiji	3.7–4.8	Vessel and shore fishing
[75]	St. Croix	6.7	Mixed
[75]	St. Thomas and St. John	8.3	Mixed
[76]	Kiribati	5	Artisanal tuna
[77]	Kiribati	5.51	Ocean
[77]	Kiribati	2.49	Reef
[77]	Kiribati	3.55	Lagoon
[77]	Kiribati	2.18	Collecting
[78]	Guatemala	12	Shark
[79]	Guatemala	24	Nets and handlines
[80]	Honduras	4–6	Diving
[81]	Honduras	4–5	Castnets
[79]	Honduras	6–12	Mixed
[81]	Honduras	2.5–3	Trap
[82]	Jamaica	7	Diving
[83]	Madagascar	6–11	Traditional
[83]	Madagascar	5–7	Travel time – Mixed
[84]	Madagascar	2–3	Gleaning
[85]	Madagascar	5	Mixed
[86]	Madagascar	7–10	Mixed
[87]	Madagascar	12–20	Shark
[88]	Nicaragua	12	Mixed
[89]	Nicaragua	9	Castnets
[90]	Niue	5	Mixed
[91]	Niue	4	Mixed
[92]	Marshall Islands	1–5	Finfish
[92]	Marshall Islands	3	Diving
[92]	Marshall Islands	5–6	Lobster
[92]	Marshall Islands	2–4	Invertebrates

References

- [1] W.W.L. Cheung, V.W.Y. Lam, J.L. Sarmiento, K. Kearney, R. Watson, D. Zeller, D. Pauly, Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change, *Glob. Chang. Biol.* 16 (2010) 24–35, <https://doi.org/10.1111/j.1365-2486.2009.01995.x>.
- [2] W.W.L. Cheung, V.W.Y. Lam, J.L. Sarmiento, K. Kearney, R. Watson, D. Pauly, Projecting global marine biodiversity impacts under climate change scenarios, *Fish. Fish.* 10 (2009) 235–251, <https://doi.org/10.1111/j.1467-2979.2008.00315.x>.
- [3] E. Chassot, S. Bonhommeau, N.K. Dulvy, F. Mélin, R. Watson, D. Gascuel, O. Le Pape, Global marine primary production constrains fisheries catches, *Ecol. Letters* 13 (2010) 495–505, <https://doi.org/10.1111/j.1461-0248.2010.01443.x>.
- [4] E.H. Allison, A.L. Perry, M.C. Badjeck, W. Neil Adger, K. Brown, D. Conway, A.S. Halls, G.M. Pilling, J.D. Reynolds, N.L. Andrew, N.K. Dulvy, Vulnerability of national economies to the impacts of climate change on fisheries, *Fish. Fish.* 10 (2009) 173–196, <https://doi.org/10.1111/j.1467-2979.2008.00310.x>.
- [5] D. Pauly, A. Ulman, C. Piroddi, E. Bultel, M. Coll, “Reported” versus “likely” fisheries catches of four Mediterranean countries, *Sci. Mar.* 78 (2014) 11–17, <https://doi.org/10.3989/scimar.04020.17A>.
- [6] T.F. Stocker, D. Qin, G.K. Plattner, M.M.B. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, P.M. Midgley, *Clim. Change 2013 Phys. Sci. basis: Work. Group I Contrib. the fifth Assess. Report. Intergov. Panel Clim. Change* (2013), <https://doi.org/10.1017/CBO9781107415324>.
- [7] J.D.K. Wilson, Fuel and financial saving for operators on small fishing vessel, 1999.
- [8] P.H. Tyedmers, R. Watson, D. Pauly, Fueling global fishing fleets, *AMBIO A J. Hum. Environ.* 34 (2005) 635–638, [https://doi.org/10.1639/0044-7447\(2005\)034\[0635:FGFF\]2.0.CO;2](https://doi.org/10.1639/0044-7447(2005)034[0635:FGFF]2.0.CO;2).
- [9] J. Driscoll, P. Tyedmers, Fuel use and greenhouse gas emission implications of fisheries management: the case of the new england atlantic herring fishery, *Mar. Policy* 34 (2010) 353–359, <https://doi.org/10.1016/j.marpol.2009.08.005>.
- [11] P.H. Tyedmers, Fisheries and Energy Use, *Encycl. Energy* 2 (2004) 683–693, <https://doi.org/10.1016/B0-12-176480-X/00204-7>.
- [12] R.W.R. Parker, L. Vázquez-Rowe, P.H. Tyedmers, Fuel performance and carbon footprint of the global purse seine tuna fleet, *J. Cleaner Production* 103 (2015) 517–524, <https://doi.org/10.1016/j.jclepro.2014.05.017>.
- [13] R.W.R. Parker, P.H. Tyedmers, Fuel consumption of global fishing fleets: current understanding and knowledge gaps, *Fish. Fish.* 16 (2014) 684–696, <https://doi.org/10.1111/faf.12087>.
- [14] R.W.R. Parker, J.L. Blanchard, C. Gardner, B.S. Green, K. Hartmann, P.H. Tyedmers, R.A. Watson, Fuel use and greenhouse gas emissions of world fisheries, *Nat. Clim. Chang* 8 (2018) 333–337, <https://doi.org/10.1038/s41558-018-0117-x>.
- [15] D. Pauly, D. Zeller, Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining, *Nat. Commun.* 7 (2016), <https://doi.org/10.1038/ncomms10244>.
- [16] D. Zeller, D. Pauly, Reconstruction of marine fisheries catches for key countries and regions (1950–2005), *Fish. Cent. Res. Rep.* 15 (2007) 168.
- [17] T. Cashion, D. Al-Abdulrazzak, D. Belhabib, B. Derrick, E. Divovich, D.K. Moutopoulos, S.-L. Noël, M.L.D. Palomares, L.C.L. Teh, D. Zeller, D. Pauly, Reconstructing global marine fishing gear use: catches and landed values by gear type and sector, *Fish. Res.* 206 (2018) 57–64, <https://doi.org/10.1016/J.FISHRES.2018.04.010>.
- [18] D. Zeller, T. Cashion, M. Palomares, D. Pauly, Global marine fisheries discards: a synthesis of reconstructed data, *Fish. Fish.* 19 (2018) 30–39, <https://doi.org/10.1111/faf.12233>.
- [19] D. Zeller, M.L.D. Palomares, A. Tavakolie, M. Ang, D. Belhabib, W.W.L. Cheung, V.W.Y. Lam, E. Sy, G. Tsui, K. Zylich, D. Pauly, Still catching attention: Sea Around Us reconstructed global catch data, their spatial expression and public accessibility, *Mar. Policy* 70 (2016) 145–152, <https://doi.org/10.1016/j.marpol.2016.04.046>.
- [20] J.A. Anticamara, R. Watson, A. Gelchu, D. Pauly, Global fishing effort (1950–2010): trends, gaps, and implications, *Fish. Res.* 107 (2011) 131–136, <https://doi.org/10.1016/j.fishres.2010.10.016>.
- [21] IMO, International Convention on Tonnage Measurement of Ships, London. https://www.jus.uio.no/english/services/library/treaties/07/7-04/imo_tonnage.xml, 1969.
- [22] FAO, Handbook of Fishery Statistical Standards, Rome. www.fao.org/cwp-on-fishery-statistics/handbook/en/.
- [23] D.A. Kroodsma, J. Mayorga, T. Hochberg, N.A. Miller, K. Boerder, F. Ferretti, A. Wilson, B. Bergman, T.D. White, B.A. Block, P. Woods, B. Sullivan, C. Costello, B. Worm, Tracking the global footprint of fisheries, *Science* 359 (80) (2018) 904–908, <https://doi.org/10.1126/SCIENCE.AAO5646>.
- [24] K. Greer, Considering the “Effort Factor” in fisheries: a methodology for reconstructing global fishing effort and carbon dioxide emissions, 1950 - 2010, University of British Columbia, 2014.
- [25] D. Belhabib, K. Greer, D. Pauly, Trends in industrial and artisanal catch per effort in West African fisheries, *Conserv. Lett.* 0 (2017) 1–10, <https://doi.org/10.1111/conl.12360>.
- [26] R.G. Latorre, J.P. Cardella, Development of an emission assessment scheme for a fishing vessel diesel propulsion engine, *J. Eng. Marit. Environ.* 222 (2008) 163–169, <https://doi.org/10.1243/14750902JEME66>.
- [27] F. Bastardie, J.R. Nielsen, B.S. Andersen, O.R. Eigaard, Effects of fishing effort allocation scenarios on energy efficiency and profitability: an individual-based model applied to Danish fisheries, *Fish. Res.* 106 (2010) 501–516, <https://doi.org/10.1016/j.fishres.2010.09.025>.
- [28] O. Gulbrandsen, Fuel savings for small fishing vessels. <http://www.fao.org/docrep/017/i2461e/i2461e00.htm>.
- [29] G. Thomas, D. O’Doherty, D. Sterling, C. Chin, Energy audit of fishing vessels, *Proc. Inst. Mech. Eng. Part M J. Eng. Marit. Environ.* 224 (2010) 87–101, <https://doi.org/10.1243/14750902JEME186>.
- [30] K.E. Abernethy, P. Trebilcock, B. Kebede, E.H. Allison, N.K. Dulvy, Fuelling the decline in UK fishing communities? *ICES J. Mar. Sci.* 67 (2010) 1076–1085, <https://doi.org/10.1016/j.icesjms.2010.09.289>.
- [31] J.D.K. Wilson, Fuel and financial savings for operators of small fishing vessels, *FAO Fish. Tech. Pap.* (1999) 46, <https://doi.org/10.1007/s13398-014-0173-7.2>.

- [32] H.C. Curtis, K. Graham, T. Rossiter, Options for Improving Fuel Efficiency in the UK Fishing Fleet, 2006.
- [33] J.J. Corbett, H.W. Koehler, Updated emissions from ocean shipping, *J. Geophys. Res.* 108 (2003) 9, <https://doi.org/10.1029/2003JD003751>.
- [34] EPA, In-Use Marine Diesel Fuel (EPA420-R-99-027), Fairfax, 1999.
- [35] S.B. Dalsøren, M.S. Eide, Ø. Endresen, A. Mjelde, G. Gravir, I.S.A. Isaksen, Update on emissions and environmental impacts from the international fleet of ships: the contribution from major ship types and ports, *Atmos. Chem. Phys.* 9 (2009) 2171–2194, <https://doi.org/10.5194/acp-9-2171-2009>.
- [36] Ø. Endresen, E. Sørsgård, H.L. Behrens, P.O. Brett, I.S.A. Isaksen, A historical reconstruction of ships' fuel consumption and emissions, *J. Geophys. Res. Atmos.* 112 (2007) 1–17, <https://doi.org/10.1029/2006JD007630>.
- [37] F. Ziegler, P.A. Hansson, Emissions from fuel combustion in Swedish cod fishery, *J. Clean. Prod.* 11 (2003) 303–314, [https://doi.org/10.1016/S0959-6526\(02\)00050-1](https://doi.org/10.1016/S0959-6526(02)00050-1).
- [38] M. Winther, U. of A.-D. National Environmental Research Institute, Fuel consumption and emissions from navigation in Denmark from 1990–2005 - and projections from 2006–2030, 2007.
- [39] Netherlands National Water Board, Exhaust from recreational boats in cooperation with DELTARES and TNO, Emiss. Estim. Diffus. Sources - Netherlands Emiss. Invent, 2008.
- [40] EPA, Calculations and references. <<http://www.epa.gov/cleanenergy/energy-resources/refs.html>>.
- [41] CarbonFund, CarbonFund Carbon Calculator 10–13, 2014.
- [42] Carbon Trust, Conversion factors: Energy and carbon conversions, 2013 update, Carbon Trust 2013 17–171. doi: [10.1016/B978-0-12-401720-7.00015-0](https://doi.org/10.1016/B978-0-12-401720-7.00015-0), 2013.
- [43] F. Ziegler, J.L. Eichelsheim, A. Emanuelsson, A. Flysjö, V. Ndiaye, M. Thrane, Life Cycle Assessment of southern pink shrimp products from Senegal. An environmental comparison between artisanal fisheries in the Casamance region and a trawl fishery based in Dakar. <<http://www.fao.org/docrep/012/i0910e/i0910e00.htm>>.
- [44] F. Ziegler, A. Emanuelsson, J.L. Eichelsheim, A. Flysjö, V. Ndiaye, M. Thrane, Extended life cycle assessment of southern pink shrimp products originating in senegalese artisanal and industrial fisheries for export to Europe, *J. Ind. Ecol.* 15 (2011) 527–538, <https://doi.org/10.1111/j.1530-9290.2011.00344.x>.
- [45] I. Vázquez-Rowe, M.T. Moreira, G. Feijoo, Carbon footprint analysis of goose barnacle (*Pollicipes pollicipes*) collection on the Galician coast (NW Spain), *Fish. Res.* 143 (2013) 191–200, <https://doi.org/10.1016/j.fishres.2013.02.009>.
- [46] U. Winther, F. Ziegler, E.S. Hognes, A. Emanuelsson, V. Sund, H. Ellingsen, Carbon footprint and energy use of Norwegian seafood products, 2009.
- [47] C.J. Cleveland, R.U. Ayres, *Encyclopedia of Energy*, Elsevier Academic Press, Boston, 2004.
- [48] P. Tyedmers, *Energy Consumption By North Atlantic Fisheries*, in: D. Zeller, R. Watson, D. Pauly (Eds.), *Fish. Impacts North Atl. Ecosyst. Catch, Effort Natl. Datasets*, Fisheries Centre Research Reports, Vancouver, BC, 2001, pp. 12–34.
- [49] Ø. Endresen, E. Sørsgård, J. Sundet, S. Dalsøren, I. Isaksen, T. Berglen, Emission from international sea transportation and environmental impact, *J. Geophys. Res.* 108 (2003) 1–22, <https://doi.org/10.1029/2002JD002898>.
- [50] M.A. DeLuchi, Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity, 1991.
- [51] T.R. Lakshmanan, X. Han, Factors underlying transportation CO₂ emissions in the USA: a decomposition analysis, *Transp. Res. Part D. Transp. Environ.* 2 (1997) 1–15, [https://doi.org/10.1016/S1361-9209\(96\)00011-9](https://doi.org/10.1016/S1361-9209(96)00011-9).
- [52] J.J. Corbett, J.J. Winebrake, Emissions tradeoffs among alternative marine fuels: total fuel cycle analysis of residual oil, marine gas oil, and marine diesel oil, *J. Air Waste Manag. Assoc.* 58 (2008) 538–542, <https://doi.org/10.3155/1047-3289.58.4.538>.
- [53] D. Pauly, D. Zeller, *Global atlas of marine fisheries: a critical appraisal of catches and ecosystem impacts*, Island Press, Washington, DC, 2016.
- [54] R.A. Watson, A database of global marine commercial, small-scale, illegal and unreported fisheries catch 1950–2014, *Sci. Data.* 4 (2017) 1–9, <https://doi.org/10.1038/sdata.2017.39>.
- [55] UN, Adoption of the Paris agreement, Paris. doi: FCCC/CP/2015/L.9/Rev.1, 2015.
- [56] J. Rogelj, M. Den Elzen, N. Höhne, T. Fransen, H. Fekete, H. Winkler, R. Schaeffer, F. Sha, K. Riahi, M. Meinshausen, Paris Agreement climate proposals need a boost to keep warming well below 2 °C, *Nature* 534 (2016) 631–639, <https://doi.org/10.1038/nature18307>.
- [57] D. Pauly, D. Zeller, Towards a comprehensive estimate of global marine fisheries catches, in: *glob. Atlas Mar. Fish. A Crit. Apprais. Catches Ecosyst. Impacts*, Island Press, Washington, D.C., 2016, pp. 171–181.
- [58] M. de Graaf, E. Tichelaar, E. Houtepen, D.C.M. Miller, T. Brunel, L.A.J. Nagelkerke, Status and trends reef fish and coastal fisheries Bonaire (Caribbean Netherlands): report card 2014–2015, 2016.
- [59] Central Bureau of Statistics Aruba, Fourth Population and Housing Census, Oranjestad, 2001.
- [60] J.S. Zaneveld, *The fishery resources and industries of the Netherland Antilles*, in: *Proc. Gulf Caribb. Fish. Institute 14 Gulf and Caribbean Fisheries Institute, 1962*, pp. 137–171.
- [61] FAO, The first meeting of the CFMC/OPESCA/WECAFC/CFRM Working Group on Queen Conch, Panama City, 2012.
- [62] A.U. Perez-Cobb, et al., Artisanal Recreational Fisheries: Using a Combined Approach to Fishery Assessment Aimed at Providing Insights for Fishery Managers, *Mar. Resour. Econ.* 29 (2) (2014) 89–109, <https://doi.org/10.1086/676838>.
- [63] S. Albert, S. Aswani, P.L. Fisher, J. Albert, Keeping food on the table: human responses and changing coastal fisheries in Solomon Islands, *PLoS One* 10 (2015) 1–13, <https://doi.org/10.1371/journal.pone.0130800>.
- [64] M.V.-S. Cajiao-Jiménez, MaríaVirginia Roxana Salazar-Cambronero, I. Naranjo-Vargas, R. Arauz, Régimen legal de los recursos marinos y costeros en Costa Rica. 1ª Edición, San Jose.
- [65] J.J. Agar, J.R. Waters, M. Shivlani, T. Murray, J.E. Kirkley, D. Suman, U.S. Caribbean fish trap fishery Socioeconomic study, *Bull. Mar. Sci.* 82 (2008) 315–331.
- [66] B. Theophile, S.D. Hutchinson, Economic analysis of the targeting strategy of artisanal fishers in Dominica, *Mar. Res. Econ.* 27 (4) (2012) 323–342 <https://doi.org/10.5950/0738-1360-27.4.323>.
- [67] M. Alvard, D. Carlson, E. Mcgaffey, Using a partial sum method and GPS tracking data to identify area restricted search by artisanal fishers at moored fish aggregating devices in the commonwealth of dominica, *PLoS One* 10 (2015) 1–23, <https://doi.org/10.1371/journal.pone.0115552>.
- [68] V. Ruiz, Job satisfaction among fishers in the dominican republic, *Soc. Indic. Res.* 109 (2012) 81–94, <https://doi.org/10.1007/s11205-012-0057-1>.
- [69] S. Singh-Renton, I. Mclvor, Review of current fisheries management performance and conservation measures in the WECAFC area., Rome, 2015.
- [70] FAO, Fishing in the dominican republic, Rome, 2008.
- [71] JICA, El estudio sobre el desarrollo de la pesca artesanal en El Salvador, 2002.
- [72] S. Iwakiri, V. Ram, Types and activities of small fishing economies in the South Pacific: a case study of Fiji, *Mem. Fac. Fish. Kagoshima. Univ.* 37 (1988) 57–96 <<http://hdl.handle.net/10232/13370>>.
- [73] M. Kronen, K. Friedman, S. Pinca, L. Chapman, R. Awira, K. Pakoa, L. Vigliola, P. Boblin, F. Magron, Pacific Regional Oceanic and Coastal Fisheries Development Programme (PROCFish/C/CoFish) French Polynesia Country Report: Profiles and Results from Survey Work at Fakarava, Maatea, Mataiea, Raivavae and Tikehau, 2008.
- [74] C. Kuster, V.C. Vuki, L.P. Zann, Long-term trends in subsistence fishing patterns and coral reef fisheries yield from a remote Fijian island, *Fish. Res.* 76 (2005) 221–228, <https://doi.org/10.1016/j.fishres.2005.06.011>.
- [75] M. Valdés-pizzini, J.J. Agar, K. Kitner, C. García-Quijano, M. Tust, F. Forrester, Cruzan Fisheries: A rapid assessment of the historical, social, cultural and economic processes that shaped coastal communities' dependence and engagement in fishing in the island of St. Croix, U. S. Virgin Islands. NOAA Series on U.S. Caribbean Fishing, 2010.
- [76] T. Riinga, Kiribati Fisheries Report, Noumea, New Caledonia, 2005.
- [77] B.M. Yee-Ting, *Fish. data Collect. South Tarawa - A 4 Mon. Summ. data Mon. Sept.-Dec.* (1985) 24.
- [78] UNIPESCA-MAGA, Plan de Acción Nacional para la Conservación y Ordenación de Tiburón. Guatemala, 2008.
- [79] C.S.B. Turriago, Contribución de la pesca y la acuicultura a la seguridad alimentaria y el ingreso familiar en Centroamérica, 2013.
- [80] FAO, Second Workshop on the Management of Caribbean Spiny Lobster Fisheries in the WECAFC Area. Havana, Cuba, 30 September – 4 October 2002, Rome. <<http://www.fao.org/docrep/006/Y4931B/y4931b00.htm>>.
- [81] C.J. Mackenzie, L.L. Stehlik, *The crustacean and molluscan fisheries of Honduras*, *Mar. Fish. Rev.* 58 (1996) 33–44.
- [82] R.A. Morris, Jamaica national Queen Conch (*Strombus gigas*) report, Jamaica, 2012.
- [83] J.C. Rey, *The Marine Fisheries of Madagascar*, 1982.
- [84] D.K.A. Barnes, K.A. Rawlinson, Traditional coastal invertebrate fisheries in South-Western Madagascar, *J. Mar. Biol. Assoc. U. Kingd.* 89 (2009) 1589–1596, <https://doi.org/10.1017/S0025315409000113>.
- [85] P. Doukakakis, M. Jonahson, V. Ramahery, B.J.D.D. Randriamanantsoa, S. Harding, Traditional fisheries of Antongil Bay Madagascar, *West. Indian Ocean J. Mar. Sci.* 6 (2007) 175–181.
- [86] J. Laroche, N. Ramanarivo, A preliminary survey of the artisanal fishery on coral reefs of the Tulear Region (southwest Madagascar), *Coral Reefs.* 14 (1995) 193–200, <https://doi.org/10.1007/BF00334341>.
- [87] G. Cripps, A. Harris, F. Humber, S. Harding, T. Thomas, A preliminary value chain analysis of shark fisheries in Madagascar, Ebene, Mauritius, 2015, <https://doi.org/10.1371/journal.pone.0065051>.
- [88] C. Lezama, J. Elliotts, Estudio de la pesca artesanal frente a la reserva natural Estero Padre Ramos (Comunidad Padre Ramos). El viejo, chinandega, Universidad Nacional Autónoma de Nicaragua, León, 2008.
- [89] K.M.J. Sequeira, Development of Artisanal Fishery in Rama Cay community, Atlantic Coast of Nicaragua, University of Tromsø, 2002.
- [90] P. Dalzell, S.R. Lindsay, H. Patiale, Fisheries resources survey of the island of Niue, Noumea, New Caledonia, 1993.
- [91] M. Kronen, D. Fisk, S. Pinca, F. Magron, K. Friedman, P. Boblin, R. Awira, L. Chapman, Pacific Regional Oceanic and Coastal Fisheries Development Programme (PROCFish / C / CoFish) Niue Country Report: Profile and Results From In-Country Survey Work, 2005.
- [92] S. Pinca, E. Tardy, R. Awira, M. Kronen, K. Pakoa, P. Boblin, A. Vanusea, L. Chapman, F. Lasi, F. Magron, Pacific regional oceanic and coastal fisheries development programme - Marshall Islands country report, Secretariat of the Pacific Community, Noumea, New Caledonia, 2007.